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The Economic Cost of Carbon Abatement Strategies

A Literature Review

Prepared For:
Industrial Energy Consumers of America

Prepared by:
Keybridge Research LLC

May 19, 2010

The purpose of this study is to summarize existing estimates of the costs associated with five key GHG abatement pathways.

Objective	Summarize existing estimates of the economic costs associated with key GHG abatement pathways: (1) building efficiency measures, (2) nuclear power, (3) renewable power, (4) vehicle CAFE standards, and (5) renewable fuels.* These five technology pathways were selected because they are estimated to be the pathways through which the largest emissions reductions will be achieved as a result of national legislation passed since 2005.**
Methodology	• Identify, review, and report published estimates from credible academic, industry, and government sources and document key assumptions.*** • Where appropriate, convert unit cost estimates (e.g., $ per MWh) to GHG abatement cost estimates (i.e., $ per metric ton of CO_2-e avoided) using a standard set of assumptions based on the EIA's Annual Energy Outlook 2010. • Convert all cost estimates to 2010 dollars.
Key Findings	• Estimates range from -$426 to $470 per ton of CO_2-e avoided. Most estimates cluster between -$100 and $100 per ton of CO_2-e avoided. • Energy efficiency measures in the buildings and transportation sectors tend to result in negative abatement costs (i.e., savings). • Measures involving greater utilization of low-carbon energy sources (e.g., nuclear power, renewable power, renewable fuels) tend to result in positive abatement costs.

* *Abatement cost estimates do not include the impact of government incentives that support individual technologies (e.g. production tax credits, loan guarantees, etc…) or government disincentives that discourage certain technologies (e.g. gasoline taxes, carbon prices, etc…). For reference purposes, the impact of a $10 carbon price on the costs of various fuels and electricity is shown in the Appendix.*

** *See Keybridge Research (May 2010), Taking Stock on Climate: Quantifying GHG Emissions Reductions Associated with Existing Sectoral Energy & Climate Policies.*

*** *This literature review documents the key assumptions associated with each estimate and, when necessary, converts cost estimates into a common metric (i.e., 2010$ per ton of CO_2-e avoided). It does not, however, attempt to harmonize assumptions across studies or abatement strategies. Consequently, direct comparisons of abatement cost estimates should only be made in the context of their differing assumptions.*

The study relies on cost estimates from a range of academic, industry, and government sources.

McKinsey&Company

ACEEE
American Council for an Energy-Efficient Economy

eia

CONGRESSIONAL BUDGET OFFICE

The Brattle Group
ECONOMIC AND FINANCIAL EXPERTS

LAZARD

Bloomberg
NEW ENERGY FINANCE

MIT
Massachusetts Institute of Technology

IAAE

ipcc
INTERGOVERNMENTAL PANEL ON climate change

NEI
NUCLEAR ENERGY INSTITUTE

EPRI
Electric Power Research Institute

NHTSA
www.nhtsa.gov

NRC The National Research Council

When necessary, cost estimates were converted to a common metric ($ per ton CO_2-e avoided) using the following assumptions.*

Renewable & Nuclear Power: Cost estimates in $ per MWh were converted to $ per metric ton of CO_2-e avoided based on the following assumptions:

- Nuclear and renewable power sources are carbon free.
- Renewable and nuclear power sources displace new coal-fired power plant generation capacity. Unless otherwise noted, the cost of new coal-fired power generation was taken from the same study that provided the cost estimate for the renewable or nuclear power source.
- New coal plants are assumed to emit 0.89 tons of CO_2-e per MWh, as derived from plant efficiency and fuel emissions factors provided by the EIA.

Building Efficiency: Cost estimates in $ per MWh or $ per mmBtu of natural gas consumption avoided were converted to $ per metric ton of CO_2-e avoided based on the following assumption:

- Reduced electricity consumption displaces new coal-fired power plant generation capacity.
- Delivered natural gas prices equal $5-$8 per mmBtu.
- Natural gas emissions factor equals 56 kg per mmBtu.

Renewable Fuels: Cost estimates in $ per liter or $ per gallon were converted to $ per metric ton of CO_2-e avoided based on the following assumptions:

- For studies that estimate current or past renewable fuel production costs, gasoline (or diesel) production costs were taken from the EIA's Annual Energy Review. Gasoline costs were calculated as refiners' prices less refiners' margin.
- For studies that provide projections of future biofuels production costs, gasoline (or diesel) production costs derived from the 2010 Annual Energy Outlook were used.

CAFE Standards: Cost estimates of $ per vehicle were converted to $ per metric ton of CO_2-e avoided based on the following assumptions:

- VMT and fuel economy assumptions were taken directly from the study that provided the cost estimate.
- Gasoline emissions factor equals 8.8 kg of CO_2-e per gallon; Diesel emissions factor equals 10.1 kg of CO_2-e per gallon.

COST ESTIMATES: BUILDING EFFICIENCY MEASURES

	Source	Cost (2010$ per Ton CO_2-e Avoided)	Key Assumptions & Notes
Lighting	International Energy Agency (2006a)	-$174	Estimate is a global average for 2008-2030, not a U.S. average
Lighting	McKinsey & Company (2007)	-$97	Projection for 2030; Replacement bulbs include compact fluorescent and LEDs
Lighting	Bloomberg (2010)	-$42	Projection for 2020
Elec-tronics	McKinsey & Company (2007)	-$104	Projection for 2030
Building Shell	McKinsey & Company (2007)	-$47	Projection for 2030; Estimate includes new builds and retrofits; Input assumptions unclear
Building Shell	Bloomberg (2010)	$20	Projection for 2020; Estimate only includes retrofits; Input assumptions unclear
HVAC Equipment	International Energy Agency (2006b)	-$95 to -$72	U.S. estimates in 2004-05 of specific AC systems in specific climates
HVAC Equipment	McKinsey & Company (2007)	$50	Projection for 2030
General Energy Efficiency Measures	Lazard (2008)	*-$84 to -$27**	Projection for 2010; Cost of various measures outlined in the National Action Plan for Energy Efficiency
General Energy Efficiency Measures	American Council for an Energy Efficient Economy (2009) - Natural Gas	*-$74 to -$20**	Average of multiple cost estimates of 6 natural gas utility rate-payer funded programs in different states in 2003-08; Compared to delivered natural gas prices of $5/mmBtu and $8/mmBtu
General Energy Efficiency Measures	American Council for an Energy Efficient Economy (2009) – Electricity	*-$71**	Average of cost estimates of electric utility rate-payer funded programs in 14 states in 2003-08; Economic life: 10-15 yrs; Discount rate: 5%; Cost of new coal power not available in this study; EIA (2009) cost was used.
General Energy Efficiency Measures	International Panel on Climate Change (2007)	< $0	Projection for 2030; The IPCC estimates that 1.3 GT CO_2 reductions can be achieved in OECD countries for negative economic costs

**Abatement cost estimates not given on a per ton of CO_2 basis. Estimates were converted using levelized cost and emissions data from available sources and EIA.*

COST ESTIMATES: NUCLEAR POWER

Source	Cost (2010$ per Ton CO_2-e Avoided)	Key Assumptions & Notes
Electric Power Research Institute (2007)	$8*	Projection for 2020; Fuel Costs: $44/MWh; Economic Life: 60 yrs; Financing: 80% debt; Capacity Factor: 90%
McKinsey & Company (2007)	$10	Projection for 2030; Construction Costs (net financing cost): $3,500-$4,000/kW; Other input assumptions unclear
Energy Information Administration (2009)	$11*	Projection for 2020; Capital Costs: $3,318/kW; Variable: O&M Costs: $0.49 mills/kWh; Fixed O&M Costs: $90.02/kW (fixed); Construction Period: 6 yrs
Nuclear Energy Institute (2009)	$24 to $31*	Year Unspecified; Capital Costs: $4,300-$4,800/kW; Fuel Costs: $7.50/MWh; O&M Costs: $9.50/MWh; Construction Period: 4 yrs; Financing: 80% debt; Discount Rate: 6.5% (debt: unregulated entities), 6.0% (debt: regulated entities) to 15% (equity); Capacity factor: 90%
Massachusetts Institute of Technology (2009)	$25*	Year Unspecified; Capital Costs: $4,000/kW; Fuel Costs: $0.76/mmBtu; Construction Period: 5 yrs; Economic Life: 40 yrs; Financing: 50% debt; Discount Rate: 8% (debt) to 15% (equity); Capacity Factor: 85%
Lazard (2008)	$27 to $59*	Projection for 2010; Capital Costs: $5,750-$7,550/kW; Fixed O&M: $12.80/kW per yr; Variable O&M: $11.00/MWh; Economic Life: 20 years; Financing: 60% debt; Discount Rate: 7% (debt) to 12% (equity); Capacity Factor: 90%
Congressional Budget Office (2008)	$45*	Projection for 2015; Capital Costs: $2,358,000/MW; Fuel Costs: $8/MWh; O&M Costs: $8/MWh; Construction Period: 6 yrs; Economic Life: 40 yrs; Financing: 45% debt; Discount Rate: 8.75%-12.5% (real rate of return); Capacity Factor: 80%-90%
Bloomberg (2010)	$46	Projection for 2020; Discount Rate: 6%; Other input assumptions unclear

**Abatement cost estimates not given on a per ton of CO_2 basis. Estimates were converted using levelized cost and emissions data from available sources and EIA.*

COST ESTIMATES: RENEWABLE POWER - WIND

	Source	Cost (2010$ per Ton CO_2-e Avoided)	Key Assumptions & Notes
Onshore	Lazard (2008)	$17 to $86*	Projection for 2010; Capital Costs: $1,900-$2,500/kW; O&M Costs: $40-$50/kW per yr; Financing: 60% debt; Discount Rate: 7% (debt) to12% (equity); Capacity Factor: 20%-23%; Capacity Factor: 28%-36%
Onshore	Bloomberg (2010)	$20 to $43	Projection for 2020; Discount rate: 6%; Other input assumptions unclear
Onshore	McKinsey & Company (2007)	$22	Projection for 2030; Installed Capacity (required to capture abatement potential): 116 GW; Other input assumptions unclear
Onshore	The Brattle Group (2010)[2]	$40*	Projection for 2013; Capital costs: $2000-$2550/kW; O&M costs: $30.5/kW per yr; Non-Renewable electricity costs: $76.6/kWh; Grid emissions: 0.43 MT CO2e/MWh; Capacity factor: 32%; Nameplate capacity: 40MW
Onshore	Energy Information Administration (2009)	$54*	Projection for 2020; Capital Costs: $1,923/kW; O&M Costs: $30.30/kW/yr; Other input assumptions unclear
Onshore	Dobesova, Apt, Lave (2006)[1]	$56*	Estimate for 2002; Capital Costs: $1000/kWh; O&M Costs: $25/kW/yr; Transmission Costs: $0.09 cents/kWh; Nameplate Capacity: 942 MW
Onshore	Electric Power Research Institute (2007)	$72*	Projection for 2020; Nameplate Capacity: 100MW; Capacity Factor: 32.5&%; Cost estimates reflect a full portfolio scenario, which allows costs to decline faster than in limited portfolio scenario
Offshore	McKinsey & Company (2007)	$46	Projection for 2030; Other input assumptions unclear
Offshore	Energy Information Administration (2009)	$150*	Projection for 2020; Capital Costs: $3,851/kW; O&M Costs: $89.48/kW/yr
Offshore	The Brattle Group (2010)[2]	$241*	Projection for 2013; Capital Costs: $4500-$5500/kW; O&M Costs: $30.5/kW per yr; Non-renewable electricity costs: $76.6/kWh; Grid Emissions: 0.43 MT CO_2-e/MWh; Capacity Factor: 37%

**Abatement cost estimates not given on a per ton of CO_2 basis. Estimates were converted using levelized cost and emissions data from available sources and EIA.*
[1] Study specific to Texas wind-generated electricity in 2002
[2] Study specific to Connecticut electric power sector

COST ESTIMATES: RENEWABLE POWER – SOLAR PHOTOVOLTAIC

Source	Cost (2010$ per Ton CO_2-e Avoided)	Key Assumptions & Notes
McKinsey & Company (2007)	$32	Projection for 2030; Abatement costs can vary by as much as $30/ton CO2e due to regional differences, such as the intensity of solar radiation (which impacts capacity factors) as well as installation costs
Bloomberg (2010)	$96 to $147	Projection for 2020; Discount Rate: 6%; Other input assumptions unclear
Lazard (2008)	$193 to $301*	Projection for 2010; Capital Costs: $3,500-$4,000/kW; O&M Costs: $25/kW per yr; Economic Life: 20 years; Financing: 60% debt; Discount Rate: 7% (debt) to 12% (equity); Capacity Factor: 30%-23%
Energy Information Administration (2009)	$327*	Projection for 2020; Capital Costs: $6,036/kW; O&M Costs: $11.68/kW per yr; Other input assumptions unclear

**Abatement cost estimates not given on a per ton of CO_2 basis. Estimates were converted using levelized cost and emissions data from available sources and EIA.*

COST ESTIMATES: RENEWABLE POWER - BIOMASS

Source	Cost (2010$ per Ton CO_2-e Avoided)	Key Assumptions & Notes
Lazard (2008)	$1 to $56*	Projection for 2010; Economic Life: 20 yrs; Financing: 60% debt; Discount Rate: 7% (debt) to 12% (equity)
Energy Information Administration (2009)	$12*	Projection for 2020; Capital Costs: $3,766/kW; O&M costs: $64.45/kW per year; Other input assumptions unclear
The Brattle Group (2010)[2]	$34*	Projection for 2013; Capital Costs: $2500-$3500/kW; O&M Costs: 66.9/kW per yr; Non-renewable electricity costs: $76.6/kWh; Grid Emissions: 0.43 MT CO2e/MWh; Capacity Factor: 85%;
Bloomberg (2010)	$61	Projection for 2020; Discount Rate: 6%; Other input assumptions unclear
Electric Power Research Institute (2007)	$67*	Projection for 2020; Nameplate Capacity: 50 MW; Capacity Factor: 85%; Cost estimates reflect a full portfolio scenario, which allows costs to decline faster than in limited portfolio scenario

**Abatement cost estimates not given on a per ton of CO_2 basis. Estimates were converted using levelized cost and emissions data from available sources and EIA.*
[1] Additional cost of retrofitting a coal-fired power plant for cofiring biomass
[2] Study specific to Connecticut electric power sector

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COST ESTIMATES: VEHICLE CAFE STANDARDS

	Source	Cost (2010$ per Ton CO_2-e Avoided)	Key Assumptions & Notes
Passenger Cars	National Highway Traffic Safety Administration (2010)	-$316*	Projection for 2016; Capital Costs: $907/vehicle; Fuel Costs: 2007$3.27/gal; Age-weighted VMT: 161,847; Fuel Savings: 801 gal/vehicle/lifetime
Passenger Cars	Bloomberg (2010)	-$250	Projection for 2020; Other input assumptions unclear
Passenger Cars	National Research Council (2002)	-$154*	Year unspecified; Fuel Costs: $1.50/gal ; Fuel Efficiency: 32.5; VMT: yr; Discount Rate: 12%; Payback Period: 14 yrs
Passenger Cars	McKinsey & Company (2007)	-$81	Projection for 2030; Capital Costs: $700-$1400/vehicle; Fuel Costs: $59/barrel oil; Fuel Efficiency: 38 mpg
Passenger Cars	Interlaboratory Working Group (2000)	-$36*	Projection for 2010; Capital Costs: $1,488; Fuel Efficiency: 38.1 mpg; Fuel Savings: $308/yr
Light Trucks	National Research Council (2002)	-$426*	Year unspecified; Fuel Costs: $1.50/gal; Fuel Efficiency: 27.9; VMT: 15,600/yr; Discount Rate: 12%; Payback Period: 14 yrs
Light Trucks	National Highway Traffic Safety Administration (2010)	-$339*	Projection for 2016; Capital Costs: $961/vehicle; Fuel Costs: 2007$3.27/gal; Age-weighted VMT: 190,006; Fuel Savings: $1,011 gal/vehicle/lifetime
Light Trucks	Bloomberg (2010)	-$245	Projection for 2020; Other input assumptions unclear
Light Trucks	McKinsey & Company (2007)	-$69	Projection for 2030; Capital Costs: $700-$1400/vehicle; Fuel Costs: $59/barrel oil; Fuel Efficiency: 28 mpg
Light Trucks	Interlaboratory Working Group (2000)	-$45*	Projection for 2010; Capital Costs: $1,629; Fuel Efficiency: 27.7mpg; Fuel Savings: $460/yr
Both	Congressional Budget Office (2003)	$61*	Year unspecified; Fuel Costs: $1.27/gal; Capital Costs: $228/vehicle; Fuel Efficiency: 31.3 mpg cars, 24.5 mpg light trucks; Discount Rate (consumer fuel cost savings): 12%

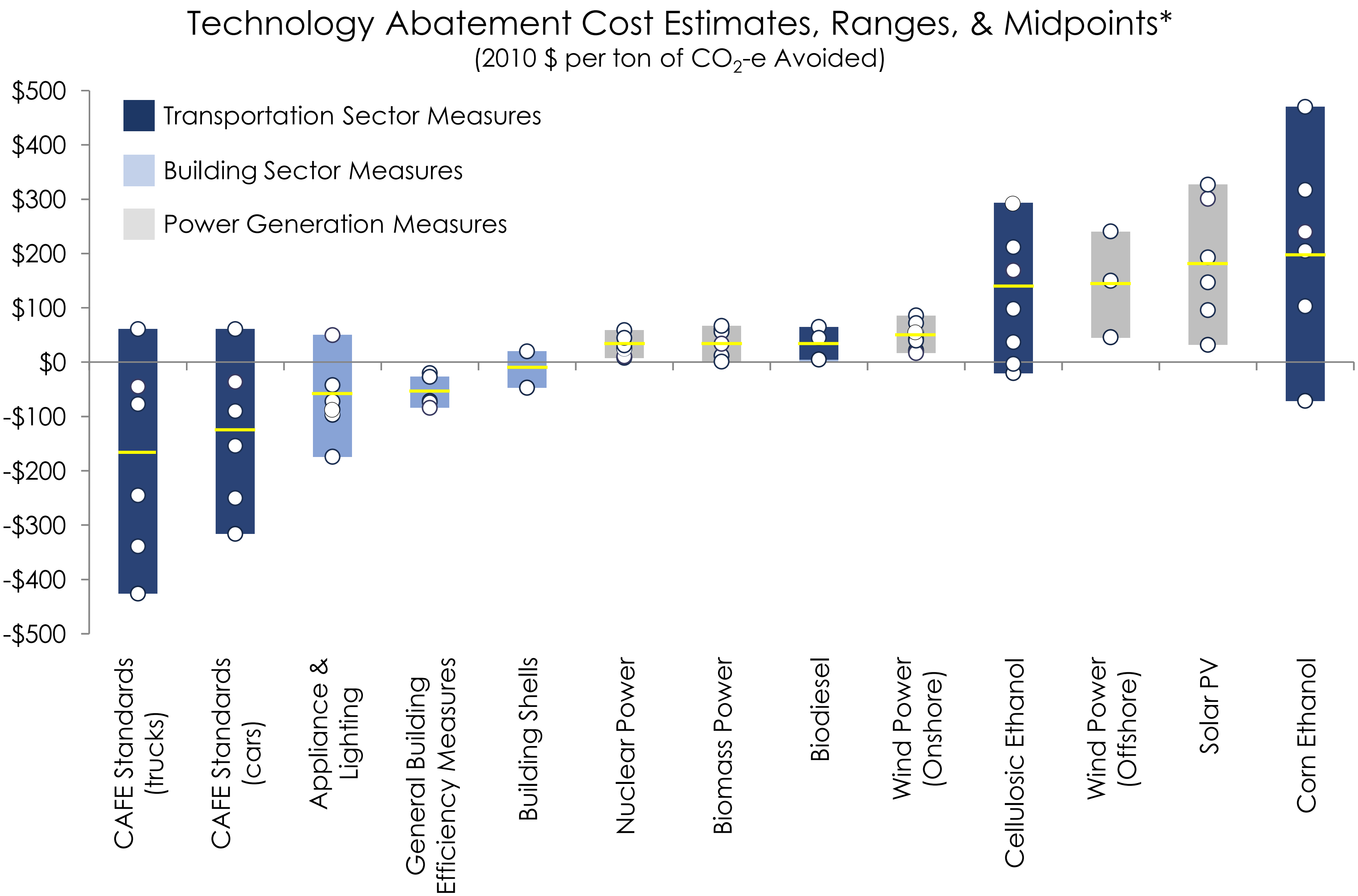
Abatement cost estimates not given on a per ton of CO_2 basis. Estimates were converted using levelized cost and emissions data from available sources and EIA.

COST ESTIMATES: RENEWABLE FUELS

	Source	Cost *(2010$ per Ton CO_2-e Avoided)*	Key Assumptions & Notes
Corn Ethanol	Dept. of Com., International Trade Admin. (2007)	-$71 to $470*	Estimate for 2007; Assumed petroleum price of $70 per barrel
	Energy Information Administration (2010)	$103*	Projection for 2020; Assumed petroleum price of $109 per barrel
	Congressional Research Service (2008)	$205*	Estimate for 2007; Assumed petroleum price of $70 per barrel
	International Energy Agency (2006)	$240*	Estimate for 2005; Assumed petroleum price of $56 per barrel
	National Commission on Energy Policy (2004)	$317*	Estimate for 2004; Assumed petroleum price of $42 per barrel
Cellulosic Ethanol	McKinsey & Company (2007)	-$20	Projection for 2030; Assumed petroleum price of $64 per barrel
	International Energy Agency (2008)	-$3 to $37*	Projection for 2020; Assumed petroleum price of $109 per barrel
	Energy Information Administration (2010)	$98*	Projection for 2020; Assumed petroleum price of $109 per barrel
	National Commission on Energy Policy (2004)	$169*	Estimate for 2004; Assumed petroleum price of $42 per barrel
	Goldemberg (2007)	$212*	Estimate for 2006; Assumed petroleum price of $65 per barrel
	Dept. of Com., International Trade Admin. (2007)	$293*	Estimate for 2007; Assumed petroleum price of $70 per barrel
Biodiesel	International Energy Agency (2008)	$5 to $65*	Projection for 2020; Assumed petroleum price of $109 per barrel
	Energy Information Administration (2010)	$45*	Projection for 2020; Assumed petroleum price of $140 per barrel

**Abatement cost estimates not given on a per ton of CO_2 basis. Estimates were converted using levelized cost and emissions data from available sources and EIA.*

SUMMARY: ALL CATEGORIES



*Abatement cost estimates do not include the direct impact of government incentives and disincentives that may alter the cost structure of individual technologies.

LIMITATIONS, QUALIFICATIONS, & UNCERTAINTIES

- The estimates presented in this study are based on a literature review. The reported estimates from each source were not verified or otherwise validated by independent Keybridge analysis.
- The sources referenced employ different methodologies and assumptions.
  - The studies assume different deployment levels. It is likely the that level of deployment (particularly for emerging technologies) will have a significant impact on technology costs through learning by doing, economies of scale, feedstock price pressures, and exhaustion of technology options.
  - The sources referenced were conducted at different times and estimate technology costs on different time horizons. For example, some calculate technology costs at the time of the study or the recent past by reviewing observed cost data while others project technology costs for future periods.
  - Most estimates measure economic costs from the perspective of the immediate technology consumer: building owners that pay their own energy bills (building efficiency), electric power consumers (nuclear and renewable power), automobile consumers (CAFE standards), and refiners of liquid fuels (renewable fuels). In general, the estimates may not reflect the full net cost to society of each measure, particularly indirect costs and benefits such as health or safety impacts.
  - Most of the studies do not provide information about what the technologies are assumed to be displacing (i.e., they do not identify a baseline scenario or technology). Where necessary, costs and emissions impacts were measured relative to technologies that are either the lowest cost alternative or the dominate technology the field.
- In most instances, reported cost estimates explicitly or implicitly assume that individual abatement strategies are pursued in isolation. They do not consider the offsetting or synergistic effects that may occur when individual abatement strategies are pursued in concert.
- When necessary and appropriate, reported estimates from each source were converted into a common currency (i.e., 2010$) and GHG impact metric (i.e., $ per ton of CO_2-e avoided). Otherwise, no attempt was made to standardize the underlying assumptions across estimates. Consequently, direct comparisons of abatement cost estimates should only be made within the context of their differing assumptions.

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APPENDIX: ENERGY PRICES WITH AND WITHOUT CARBON PRICES

Fuel	Units	2010 Price*	With a $10 Carbon Price	
			Price Increase	Percentage Increase
Gasoline	$ per gallon	$2.91	$0.09	3.0%
Crude Oil	$ per barrel	$82.00	$4.35	5.3%
Natural Gas	$ per mmBtu	$4.78	$0.53	11.1%
Coal (No Capture)	$ per short ton	$42.95	$19.05	44.4%
Electricity**	$ per MWh	$98.00	$5.74	5.9%

**Energy prices are taken from the Energy Information Administration's forecast for the second quarter of 2010 in its Short Term Energy Outlook from April 2010. Prices represent the average retail price for conventional gasoline, the average spot price for West Texas intermediate crude oil, the average delivered prices of natural gas and coal to electric power producers, and the average delivered price of electricity for all users.*

***The carbon intensity of electric power is based on the national average as projected in the 2010 AEO for 2010.*

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Keybridge Research LLC is a Washington DC based international economics and public policy consulting firm. Keybridge provides analytical support and strategic advice to a select clientele that includes Fortune 500 companies, global financial firms, G-7 governments, and premier industry associations. Our experience and expertise make us uniquely suited to assist organizations that operate at the interface of business, economics, and public policy.

Keybridge provides clients with access to a full suite of analytical services, including macroeconomic risk assessments, econometric modeling studies, policy impact studies, qualitative policy evaluations, and survey design and analysis. For clients requiring regular consultations, Keybridge offers on-going strategic advisory services in the areas of macroeconomic trends and risks, international trade and finance, and energy and environmental economics. Keybridge also assembles and manages inter-disciplinary teams of experts to conduct thought leadership projects to assist clients with building competitive advantages or reframing policy debates through the development, sharing, and application of innovative ideas. Our principals are regularly asked to present research and share insights with economic, financial, and policy audiences around the world, including corporate strategic planning committees, congressional committees, and international conferences.

KEYBRIDGE PROJECT TEAM MEMBERS

Dr. Robert F. Wescott (Principal Investigator), is President of Keybridge Research LLC. Dr. Wescott has nearly 30 years of professional experience working on macroeconomic and public policy issues. Dr. Wescott served for four years as Special Assistant to the President for Economic Policy at the White House and as Chief Economist at the President's Council of Economic Advisers. From 1982-93, he was Senior Vice President and Chief Economist at Wharton Econometrics (today IHS Global Insight), where he oversaw a staff of 60 and was responsible for all economic modeling, forecasting, and consulting operations. Dr. Wescott also was Deputy Division Chief in the Research Department of the International Monetary Fund, where he did research on global economic risks and policy challenges. In 1989-90 he was Research Director at the International Center for the Study of East Asian Development in Kitakyushu, Japan. He holds a Ph.D. in Economics from the University of Pennsylvania.

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